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Performance of Process Damping in Machining Titanium Alloys at Low Cutting Speed with Different Helix Tools

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Abstract. Titanium is a strong, lustrous, corrosion-resistant and transition metal with a silver color to produce strong lightweight alloys for industrial process, automotive, medical instruments and other applications. However, it is very difficult to machine the titanium due to its poor machinability. When machining titanium alloys with the conventional tools, the wear rate of the tool is rapidly accelerate and it is generally difficult to achieve at high cutting speed. In order to get better understanding of machining titanium alloy, the interaction between machining structural system and the cutting process which result in machining instability will be studied. Process damping is a useful phenomenon that can be exploited to improve the limited productivity of low speed machining. In this study, experiments are performed to evaluate the performance of process damping of milling under different tool helix geometries. The results showed that the helix of 42° angle is significantly increase process damping performance in machining titanium alloy.

Key Words: Titanium, Process Damping, Helix Angle, Cutting Force, Frequency Response Function

1. Introduction

Titanium's physical qualities of high strength, toughness, durability, low density, corrosion resistance and biological compatibility have made it useful in a variety of applications. Titanium is currently used in aerospace applications, automobiles, prosthetics, buildings, and sporting equipment [1]. Titanium, which weighs of forty percent less than carbon steels, can be strengthened by alloying it with elements such as aluminum and vanadium. Titanium is nonmagnetic and possesses good heat transfer properties. It has a corrosion resistance to acids, nontoxic and biocompatible [2, 3]. These properties make titanium and its alloys useful in a wide range of structural, chemical, petrochemical, marine and biomaterial applications. The most widely used titanium alloy, Ti-6Al-4V, is present in forty-five percent of industrial applications. The unique combination of this alloy's physical and mechanical properties such as workability, fabricability, along its good production experience and as well as its commercial availability allows it to be economically useful. Therefore the efficiency of titanium machining is one of the major challenges in production engineering.

The common cause of instability in metal cutting is the regenerative chatter, and this often limits the productivity of machining operations. The regenerative chatter stability boundary is known as the stability lobe diagram and is a function of depth of cut and spindle speed, as shown schematically in figure 1. It has been reported that regenerative chatter is caused by interaction between the structural dynamics of the machine tool and the dynamics of the cutting process [4]. The requirement for high productivity of machining leads to a desire to suppress chatter and various methods have been proposed. This includes adding passive or active damping [5, 6], spindle speed manipulation or variation [7,8] and alternative methods [9,10,11]. Besides the damping produced from the structure of machine tools, the machining process itself can create damping to the system through a phenomenon known as process damping. The term of process damping or also known as resistance force was introduced by Tobias and Fishwick [12] and happens when the tool's flank face or rake angle rubs against the wavy workpiece surface at low spindle speeds. At high spindle speeds, the lobbing effect can be observed, and this allows high productivity cutting to be performed on easy-to-machine materials such as aluminium alloys.

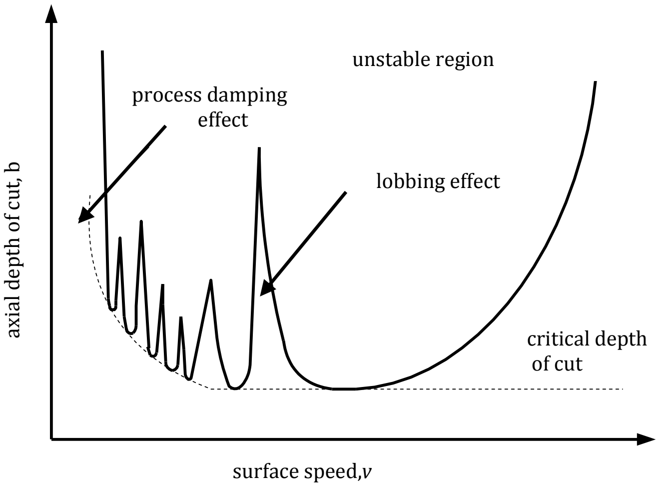


Figure 1. Process damping in stability lobe.

Unfortunately the resulting high surface speeds are incompatible with more difficult to- machine materials such as titanium and nickel based alloys. Previously, the practitioner is limited to low spindle speeds, where the chatter stability is strongly influenced by the process damping phenomenon. However, understanding of process damping remains as an unsolved problem in chatter research [13]. Most of the researcher agreed with the effect of low speed spindle to damping process however none has been reported the best tool application such as Montgomery and Altintas [14] used a model-based approach to investigate ploughing forces. Delio et al. [15] considered the wavelength of chatter vibration and the loss of process damping behavior at higher spindle speeds. Elbestawi et al. [16] modeled process damping effects when cutting aluminium and showed that the model could produce additional damping forces due to the tool flank / workpiece interference. Ranganath et al. [17] also developed a time-domain model of process-damped milling and compared the results with experimental data from an aluminium alloy workpiece. Huang and Wang [18] proposed a model that considered the consequences of chatter vibration on the effective rake and relief angles. They included additional empirical parameters in their model so that the cutting stiffness became a function of these effective angles, and thereby produced a process damping effect.

Until recently, Yusoff et al. [19] identified the significant contribution of variable helix/pitch compare to rake, relief angles and edge radius to increase process damping performance. From a practical and industrial point of view, understanding the effect of these variable helix and pitch on process damping is clearly of great importance, because it allows the practitioner to choose better tooling for specific machining problems. Therefore, the aim of the present study is to perform experimental milling experiments so that different tool helix geometries can be ranked in terms of their positive influence on process damping in milling.

2. Theory

Chatter is produced from self-excited vibration during cutting resulting in a high amplitude unstable motion. The amplitude of this motion is limited by nonlinearities such as tool loss of contact, nonlinear cutting force coefficients and nonlinear stiffness of the machine tool structure. The chatter frequency is close to a natural frequency of the system. At low speeds, the wavelength λ of these surface waves is much smaller since the wavelength is proportional to surface velocity v and inversely proportional to regenerative vibration frequency f_c , as shown by equation (1):

$$\lambda = \frac{V}{f_c} \tag{1}$$

As the spindle speed (and hence surface velocity) is reduced, the process damping phenomenon becomes sufficient for the regenerative chatter to be stabilized or suppressed as shown in figure 1. The corresponding surface vibration wavelength is given by equation (1) and is referred to as the process damping wavelength λ. The commonly proposed mechanism of process damping is shown schematically in figure 2. As each tooth removes the chip from the wavy surface, process damping forces are generated that act on the structure. The damping force corresponds to inference between tool flank face and wavy surface, where more damping force occurs at point 'B'. A ploughing force can be produced from the workpiece being deformed by the tool, whilst the surface angle changes the effective shear angle of the tool. Interference is minimized when the tool travels upwards on the wave (position 'D' in Figure 2) due to the positive slope of the machined surface. According to this concept, low relief angles should produce high ploughing forces from the engagement between tool and workpiece. Consequently, different helix angles should be considered in the evaluation of process damping.

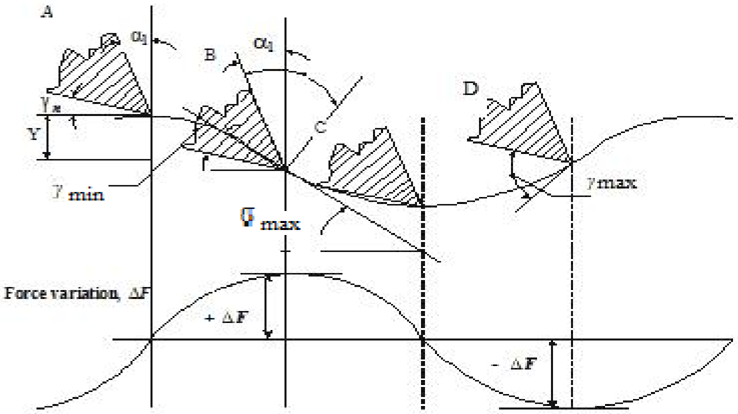


Figure 2. Process damping mechanism γ.

In the stability of high speed milling, axial depth of cut b is the most influential factor since the cutting forces are often considered in cutting force model, as shown in figure 3. This is to be given by the relationship

$$F = K_s\, b\, (Yo - Y) \tag{2}$$

where F is the cutting force, b is the axial depth of cut, K_s is the empirical cutting stiffness, and ($Yo - Y$)

is the change in surface position between current and previous cuts. In theory, the stability boundary is then independent of the feed rate despite the influence of the feed rate on the mean chip thickness. In practice, the empirical cutting stiffness K_s changes with the feed rate so that the feed rate does have some influence on the overall stability. K_s depends on K_t and K_n based on below formula

$$K_s = \sqrt{{K_t}^2 + {K_n}^2} \tag{3}$$

$$\theta = tan^{-1}\left(\frac{K_t}{K_n}\right) \tag{4}$$

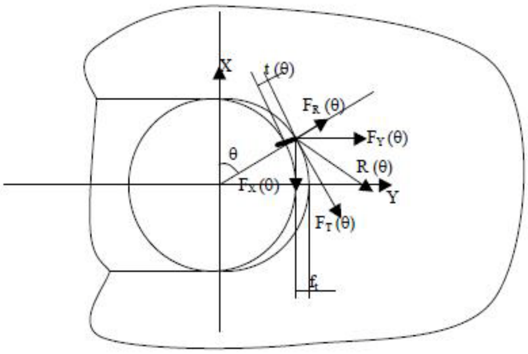


Figure 3. Model of cutting forces in milling operation [20].

This tangential cutting forces F_t, represent a resistance to workpiece rotation and constitute approximately more than twice normal cutting force. This trend will be occur in every experimental and different tools have different cutting force stiffness. Cutting force is very important thing that we need to be considered in machining process. The cutting forces that are developed during the milling process can directly or indirectly estimate process parameters such as tool wear, tool life, surface finish and also production time. Therefore it is necessary to identify the relationship between the cutting forces and uncut chip area that can be expressed as a product of the axial depth of cut and feed per tooth in order to predict cutting behaviour. During one tooth period, the average milling force in x and y direction is given by equation (5) [20].

$$\begin{aligned}\bar{F}_x &= \left\{\frac{Nbc}{8\pi}\left[K_t \cos(2\theta) - K_n\left[2\theta - \sin 2\theta\right]\right] + \frac{Nb}{2\pi}\left[-K_{te}\sin\theta - K_{ne}\cos\theta\right]\right\}_{\theta st}^{\theta ex} \\ \bar{F}_y &= \left\{\frac{Nbc}{8\pi}\left[K_n\left[2\theta - \sin(2\theta)\right]\right] + K_t\, cos(2\theta) - \frac{Nb}{2\pi}\left[K_{te}\cos\theta - K_{ne}\sin\theta\right]\right\}_{\theta st}^{\theta ex}\end{aligned} \tag{5}$$

Where K_{te} and K_{ne} represent the tangential and normal edge cutting force coefficient, while K_t and K_n represent the tangential and normal cutting force coefficient, respectively. The entry and exit angles of the cutter are $\theta_{st} = 0$ and $\theta_{ex} = \pi$, respectively. These cutting coefficients can be determined through cutting measurement with a force dynamometer and cutting certain conditions. Therefore, the average force per tooth period to be found

$$\begin{aligned}\overline{F_x} &= -\frac{mb}{4}K_n c - \frac{mb}{\pi}K_{ne} \\ \overline{F_y} &= \frac{mb}{4}K_t c - \frac{mb}{\pi}K_{te}\end{aligned} \tag{6}$$

In function of chip load *c*, equation (6) can be written as

$$\bar{F}_q = \bar{F}_{qc}C + \bar{F}_{qe}(q = x, y, z) \tag{7}$$

The experiment completes for a multiple cutting test with a range of chips load to recorded the cutting force values in x and y direction. A linear regression was then performed on the mean force values to determine cutting coefficient in equation (3) and (4) as given:

$$K_t = \frac{4F_{yc}}{Nb}, \quad K_n = \frac{4F_{xc}}{Nb}, \quad K_{te} = \frac{\pi F_{ye}}{Nb}, \quad K_{ne} = \frac{-\pi F_{xe}}{Nb} \tag{8}$$

F_{ye} and F_{xe} are determined from intersection at force axis for x and y- force data direction, while F_{yc} and F_{xc} are determined from the gradient at force axis for x and y – force data directions. However, under process-damped cutting conditions, the effect of feed rate has been observed to be significant [17]. It is useful to express the feed rate in terms of the maximum chip thickness h_{max} [18]:

$$h_{max} = fpt\sqrt{\frac{4r}{D} - \left(\frac{2r}{D}\right)^2} \tag{9}$$

Here, r is the radial immersion of the tool, and D is the tool diameter. The feed per tooth *fpt* is related to the machining feed rate *f*, number of teeth m and spindle speed n as shown by equation (10).

$$f = m \times fpt \times n \tag{10}$$

Using a high depth of cut at low cutting speed results in the chatter stability being dominated by process damping effects as shown on the left side of the stability diagram in figure 1. Meanwhile, using a low radial immersion helps to reduce the total machining forces and improves tool life. This approach will be employed in the present study in order to determine the process damping wavelength λ_c under different tool geometry and feed rate conditions.

4. Experimental Procedure

4.1. Frequency Response Function (FRF)

The experimental approach involved of the impact hammer model in which the testing applied was to measure flexure frequency response function and cutting tool frequency response function. The data acquisition system apparatus used was a Bruel & Kjaer model type 7539A 5/1 channel. Meanwhile, for an impact testing, a normal force created by using a 2302-10 Meggit hammer with vinyl tip was applied at the tool tip. The acceleration response was then captured by a 4507B Bruel & Kjaer accelerometer which was located opposite to the hammer impact point. From the frequency response function analysis, the wavelength of the vibration has been obtained.

4.2. Cutting force determination

The cutting force coefficient tests were conducted by using Haas 3 Axis CNC milling machine TM2. The average helix angles of 4 tools were measured by using an optical comparator (Mahr-MM320). Meanwhile, the force response of the cut titanium workpiece was obtained by using a Kistler Multi-Compenent Dynamometer type (9257B). The cutting condition was varied between 95mm/min and 222mm/min. The parameters used in experiment are listed in table 1. The feed rate values are dependent to the changing values of feed.

Table 1. Parameter set up in cutting force experiment.

Condition	Feed	Spindle speed (rpm)	Axial depth of cut(mm)	Radial Emmersion(%)	Feed rate (mm/min)
1	0.03	796	2	100	95
2	0.04	796	2	100	127
3	0.05	796	2	100	189
4	0.06	796	2	100	191
5	0.07	796	2	100	222

4.3. Process Damping

Process damping experiment was performed by using Haas 3 Axis CNC milling Machine TM2, as shown in figure 4. From the frequency response function , the resonant frequency obtained was used to choose a starting value for spindle speed, so that the expected wavelength of vibrations was $\lambda = 0.1$ mm. This was achieved by using both equation (1) and the relationship between tool diameter, spindle speed and surface speed. Based upon previous study [19], this initial wavelength was reported to be below the process damping wavelength λ_c. Meanwhile, the desire maximum chip thickness, the feed per tooth and hence the initial feed rate were then determined by using equations (9) and (10). A low radial width of cut ($r = 1$ mm) and large axial depth of cut ($b = 7$ mm) were used to minimize forced vibration as well as to reduce tool wear and also to prevent further damage to the tool if severe chatter occurred. The spindle speed, n and feed rate, f were incremented simultaneously by 10 percent in order to maintain constant fpt and h_{max}, until chatter was detected. Process damping performance was then evaluated in terms of λ_c from equation (1). Here, the chatter frequency was obtained from Fourier analysis of the vibration signal and the surface speed, v was determined based upon the spindle speed at which chatter occurred. The procedure was repeated for five h_{max} values in the range of 0.04 and 0.12 mm for each tool. Here, a block of titanium was mounted on a flexible structure (as shown in figure 4) and it was adapted from Yusoff et al [19]. During cutting, the vibration signal was recorded by using an accelerometer type (352C33).

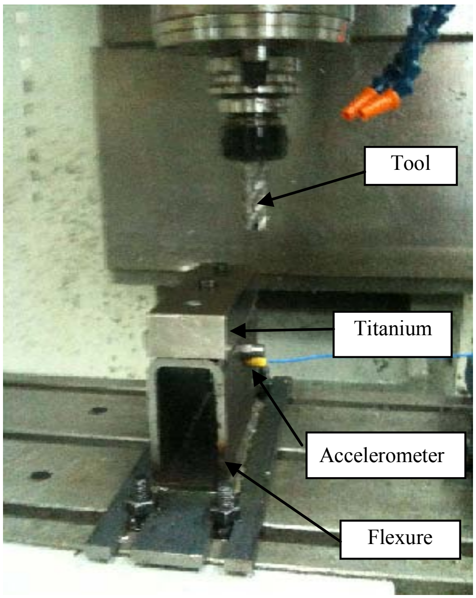


Figure 4. Experimental process damping arrangement

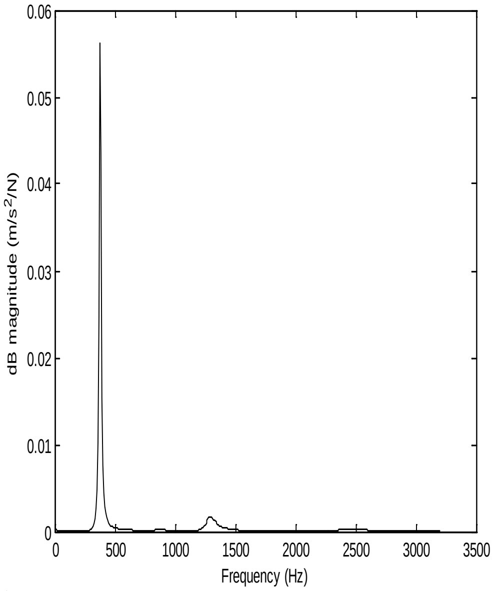


Figure 5. Frequency response function for Flexure.

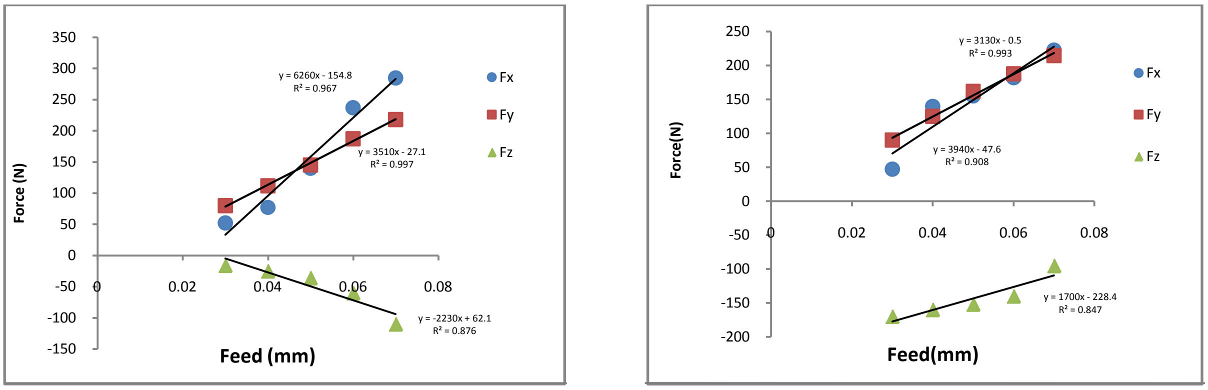
5. Result and Discussion

5.1. Frequency Response Function (FRF)

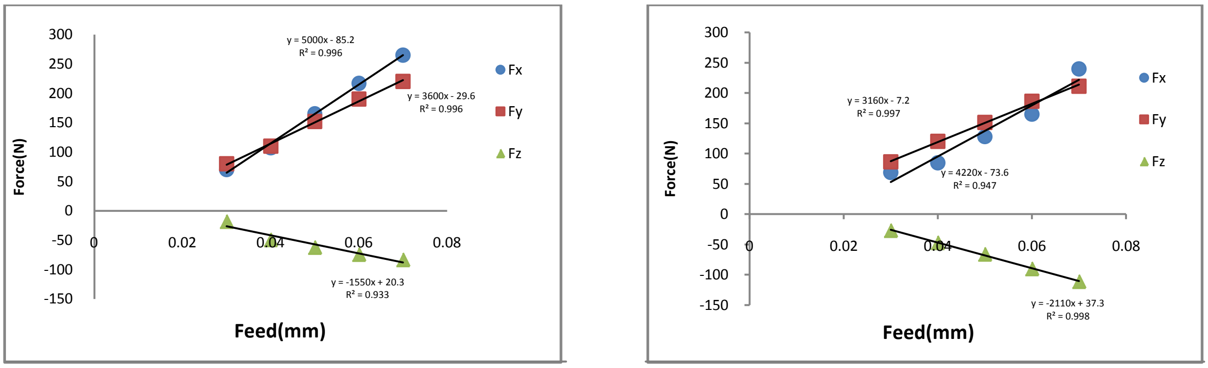
Figure 5 shows the frequency response function flexure obtained from the conducted experiment. It shows that the dominant frequency of flexure was 367 Hz. A huge distinction of frequency between tools and flexure in the frequency response function experiments is significant in order to get a dominant damping frequency from workpiece.

5.2. Cutting force experiment

In this experiment, a cutting force coefficient for each tool was measured in order to provide a clear understanding of the influence of helix geometry would have on cutting force process. The cutting force coefficient investigation was also intended to explore whether the cutting force coefficient were linear during low feed rates and also to understand whether an increase in cutting force coefficient is due to damping wavelength. From the result obtained, the average force corresponded to a particular feed rate for each point (figure 6). By using relation in equation (8) and linear regression, the cutting force coefficient values can be calculated and were summarized in table 2.



a) T1 b) T2



c) T3 d) T4

Figure 6. Cutting force coefficient linearity for each tool.

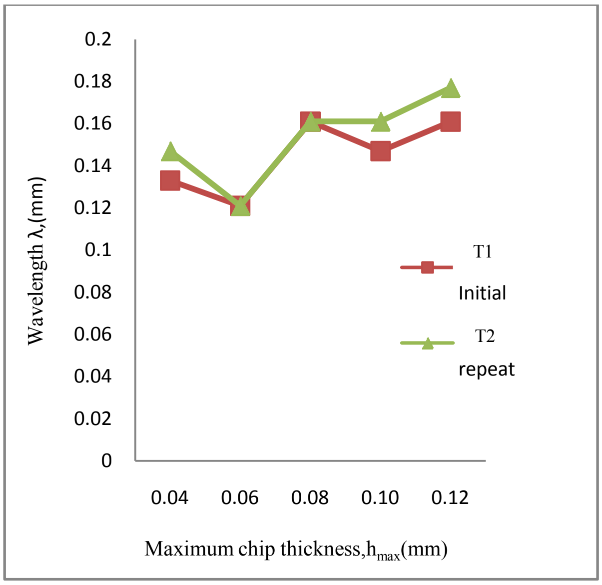
Table 2. Cutting Force Coefficient for Each Tools

Tool	Helix Angle (°)	K_t (MN/m$^{2)}$	K_n (MN/m$^{2)}$	K_s (MN/m$^{2)}$	θ (°)
T 1	37°	3510	6260	7177	29
T 2	45°	3130	3940	5032	39
T 3	42°	3600	5000	6161	36
T 4	52°	3160	2110	3799	56

5.3. Analysis of Process Damping Wavelength

Figure 7 presents the repeatability test of T1 on process damping wavelength. It can be seen that the tools indicate a repeatability error is less than 10 percent between the initial test and repeat test. By performing the repeated test after the other experiment means that, there would be a slight amount of tool wear, so the influence of this wear could be compared to the influence of the other process parameters. It is clear that even considering this repeatability error, the maximum chip thickness has very significant effect on process damping wavelength.

Figure 8 shows the comparison of the damping wavelength obtained in this study for each tool. It can be seen that tools with different helix angle have different process damping performance. Generally, the damping wavelengths are gradually increase for all tool from h_{max} 0.04 to 0.12. The lower and higher helix angle causes low damping performance at high h_{max}.



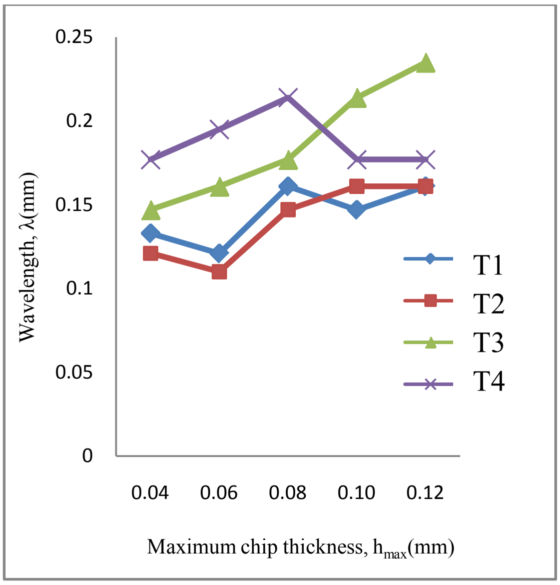


Figure 7. Repeatability of T1 on process damping wavelength.

Figure 8. Comparison damping wavelength for each tool.

In Figure 8, the best damping performance was T3. T3 was able to achieve the highest damping wavelength at h_{max} 0.10 and h_{max} 0.12 compared to T1, T2 and T4. This tool also has a steady process damping performance from h_{max} 0.04 to 0.12. It is useful to relate this result to cutting force coefficient. According to the damping model as shown in figure 2, the force coefficient on the tangent component is important to increase process damping performance. In this cases where T3 have the highest K_t compare to T1, T2 and T4, and second high K_s. This tool geometry needs high K_s and K_t to increase process damping performance. In conclusion, high process damping performance depends on cutting force coefficient and helix angles.

6. Conclusion

This paper presents a relationship between the cutting force coefficient and damping wavelength. From the data gathering in all experiments, the results have showed that this is useful relationships between damping wavelength and cutting force coefficient. The experimental data showed that T3 have the highest value of K_b, according to that T3 have the highest damping wavelength compare to the others. The results showed that the helix of 42° angle most significantly increase process damping performance in machining titanium alloy. Further work will be conducted to study the effect process damping performance due on variable helix, variable pitch and variable helix and pitch tools.

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